Chapter 10
Changing Nutrients, Oxygen and Phytoplankton in the East China Sea

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Abstract Biogeochemical processes in the East China Sea are substantially affected by anthropogenic nutrient inputs. The dramatic decadal changes in nutrient concentrations were mainly due to the increases of DIN and DIP in the Changjiang (Yangtze) River since 1980s. As a result, phytoplankton abundance increased dramatically between 1958 and 2016 in both the Changjiang Estuary and the East China Sea. Before 1980s, chain-forming diatoms were dominant, while increasing of large-cell dinoflagellates is probably related to increasing DIN/silicate ratio. Increasing nutrient input and phytoplankton abundance greatly impact seasonal hypoxia condition in the East China Sea. Hypoxia is relatively sporadic and patchy before 2013. In 2016 and 2017, hypoxic events were more severe, occurring over larger areas with dramatically lower minimum values of dissolved oxygen. Notwithstanding, occurrences of bottom hypoxia in the East China Sea are highly dynamic and are significantly influenced by episodic events such as wind mixing.

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10.1 Introduction

The East China Sea, which borders the East Asia mainland, is a marginal sea of the northwest Pacific Ocean. To the south, the sea connects to the South China Sea through the Taiwan Strait; to the northeast, to the Japan/East Sea through the Tsushima Strait. Kuroshio waters intruding through north-east Taiwan and eastbound shelf break are the major water sources. The interactions of these waters with shelf waters significantly influence the East China Sea water budget (Hsueh et al. 1992; Zhou et al. 2015), and biogeochemical cycles (Chen and Wang 1999; Lui et al. 2015). The East China Sea also receives massive inputs of fresh water, nutrients, and suspended organic matter from the Changjiang (Yangtze) River and the Qiantang River. The tremendous inputs of riverine materials trigger harmful algal blooms, and hypoxia (Liu et al. 2015a, b; Wang et al. 2017a, b; Zhou et al. 2008; Zhu et al. 2011), greatly affect carbon cycles (Chou et al. 2013; Li et al. 2018; Tseng et al. 2014), and the shelf ecosystem (Gong et al. 2011; Jiang et al. 2014), especially in plume waters.

Over the past few decades, the East China Sea shelf has experienced dramatic environmental change. Since the 1980s, the ever-expanding population and economic growth of East China, including the Changjiang River Basin have caused three to six fold increase of nutrient (nitrogen and phosphate) inputs to the Changjiang Estuary and the East China Sea (Li et al. 2007; Zhou et al. 2008). As a result, phytoplankton standing stocks and the frequency of harmful algal blooms in the sea have increased (Jiang et al. 2014; Wang and Wu 2009). In bottom waters, large-scale hypoxia has occurred frequently due to the enhanced input of organic matter from the surface phytoplankton blooms (Zhu et al. 2011; Wang et al. 2017a).

In this chapter, we review decadal changes of nutrients, phytoplankton community, and dissolved oxygen (DO) characteristic in the East China Sea (Fig. 10.1), based on data obtained from multiples research cruises. Some of these data have been reported in the literatures. For this overview, we focus on the northern East China Sea, which is strongly affected by the Changjiang River.

10.2 Nutrients

National marine surveys of Chinese seas in the 1950s (OIOSC 1964a), 1980s (Wang et al. 1991), and 2000s (Wang et al. 2011), as well as others scientific surveys have provided valuable snapshots of the spatial distributions of nutrients in the East China Sea (Chen 2009; Gong et al. 1996; Wang et al. 2003). The temporal variations, especially the decadal variations are less well documented (Chai et al. 2006; Wang et al. 2018), even though such changes are important for evaluating shelf ecosystem

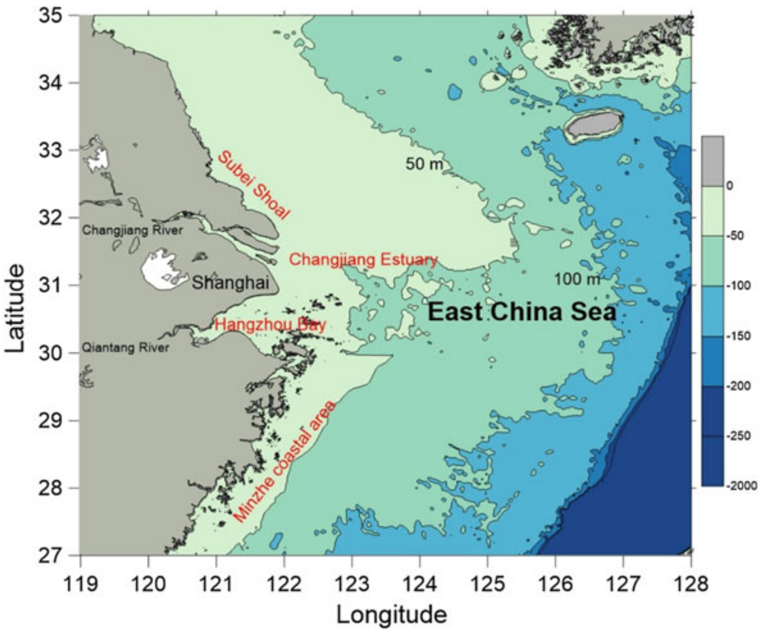

Fig. 10.1 Map of the East China Seas

status, and projecting future scenarios (Ducklow et al. 2009). In surveying historical data, we found that discussions of decadal changes in nutrient concentrations did not always include the corresponding values of salinity, which are significantly important in understanding coastal and shelf process. Here, we compare nutrient data from the 1980s and the 2000s in the East China Sea across a wide salinity range.

10.2.1 East China Sea

In the East China Sea, concentrations of dissolved inorganic nitrogen (DIN, sum of nitrate, nitrite, and ammonium) in the 2000s were much higher than that in the 1980s (Fig. 10.2a). At salinity <5, DIN concentrations in the 2000s exceeded 100 μmol L^{-1}, up from less than 60 μmol L^{-1} in the 1980s. This increase is likely caused by increasing DIN concentrations in the Changjiang River. On river-dominated shelf, where a large plume is formed by the mixing of nutrient-replete river water and relatively nutrient-poor oceanic water, plume DIN concentrations decrease sharply with increasing salinity. A salinity of 31 is often used to define the outer edge of the plume, which can sometimes reach the South Korean peninsula (Isobe and Matsuno 2008; Wang et al. 2003) and during flood years may cover an area of 141,000 km^2 (Gong et al. 2011). As shown in Fig. 10.2a, the maximum DIN concentration at the plume edge was ~16 μmol L^{-1} in the 1980s and ~25 μmol L^{-1} in the 2000s. This

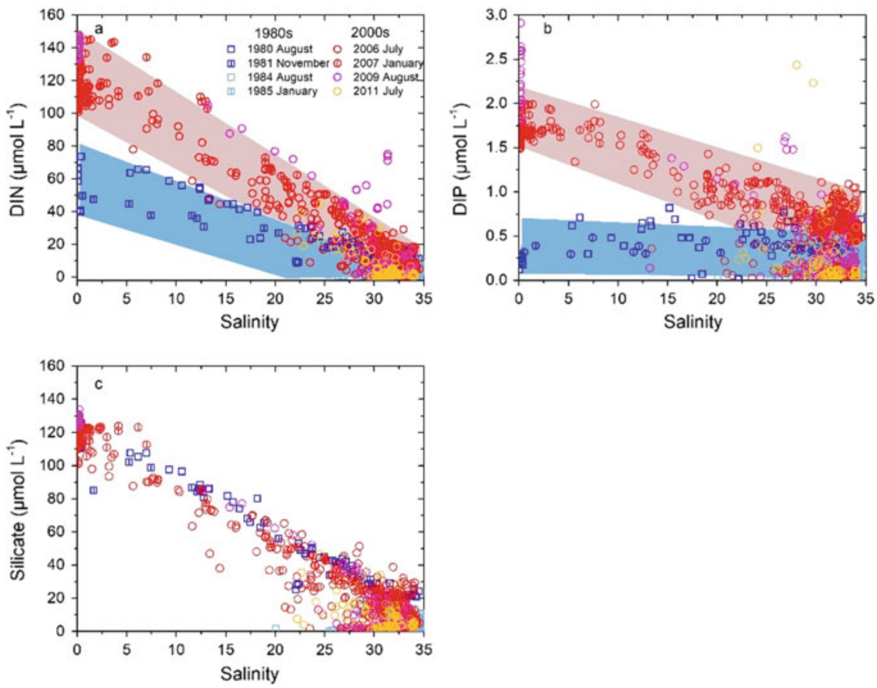

Fig. 10.2 Nutrient concentrations in the East China Sea during the 1980s and 2000s, plotted as a function of salinity: **a** DIN, **b** DIP, and **c** silicate. The blue and red envelopes on the top two panels showed concentration limits along salinity during 1980s and 2000s, respectively. Data were obtained from Edmond et al. (1985), Wang et al. (2011), Li et al. (2016), and our own unpublished work

30-year DIN increase of plume waters could be reasonably expected to significantly influence oxygen dynamics and phytoplankton community structure in the East China Sea (as discussed below) and even the Japan Sea (Chang et al. 2015). For salinity >33, no significant DIN decadal trend was found from our data set.

Similar to the case of DIN, the mixing of nutrient-poor oceanic surface waters and river waters high in dissolved inorganic phosphate (DIP) has been important in regulating concentrations in the East China Sea. DIP concentrations in the 2000s were higher than those of the 1980s (Fig. 10.2b). At low salinities, DIP concentrations in the 2000s were >1.5 μmol L^{-1}, up from <0.8 μmol L^{-1} in the 1980s. In the early 1980s, DIP concentrations were relatively constant across the wide salinity range of 5–15. In the 2000s, however, DIP generally decreased with increasing salinity over that range. Desorption of DIP from suspending sediments could also have been important (Edmond et al. 1985; Liu et al. 2016; Zhang 1996). In Changjiang Estuary surface waters, concentrations of particulate inorganic phosphate accounts for about half the concentration of DIP (Liu et al. 2016; Wang et al. 2009). At the outer edge of the river plume, DIP concentrations are usually undetectable due to phytoplankton uptake, while nitrate is still available; thus, phytoplankton growth is usually limited by the depletion of DIP (Harrison et al. 1990; Tseng et al. 2013). Phosphate-enrich bottom waters and waters transport from Taiwan Strait can be an important phosphate source to upper waters (Chen and Wang 1999; Huang et al. 2019; Li et al. 2016).

Silicate concentrations, unlike those of DIN and DIP, exhibit no notable decadal changes in the fresh water endmember (Fig. 10.2c), while they show a dramatically decreasing trend in the oceanic water endmember, indicating diatom bloom has increased because of increasing of DIN and DIP (Wang et al. 2017a). This difference seems reasonable in light of the different sources and biogeochemical processes of these nutrients. DIN and DIP concentrations have been strongly influenced by anthropogenic nutrient sources (increasing), whereas the main source of silicate is the weathering of rocks within the Changjiang river basin. The Three Gorges Dam, which was constructed across the river in 2003, has reportedly reduced downstream river sediment loads significantly (Dai et al. 2010) and possibly also river water silicate concentrations (Dai et al. 2010; Gong et al. 2006). In our East China Sea data set, however, no significant trend of decreasing silicate was found in the fresh water endmember. A longer period of observation is perhaps needed to document the potentially more subtle decadal variations of silicate concentrations in shelf waters.

10.2.2 Hangzhou Bay

Sharp increases of DIN were observed in Hangzhou Bay over the three decades of observation (Fig. 10.3a), similar to the case of the East China Sea (Fig. 10.2a). At salinity = 10, DIN concentrations were ~140 μmol L^{-1} in the 2000s, up from 20 to 80 μmol L^{-1} in the 1980s. At the mid-range salinities of 10–27, concentrations increased by a factor of 2–3, from ~30 μmol L^{-1} in the 1980s to ~70 μmol L^{-1} in the 2000s. This increase of mid-bay DIN was caused primarily by increasing concentrations in not only the Qiantang River, which flows directly into Hangzhou Bay, but also the Changjiang River to the north (Dai et al. 2014; Su and Wang 1989). In the low-salinity zone of upper Hangzhou Bay, the Changjiang influence was not likely a primary driver, as DIN concentrations there were even higher than those in the Changjiang estuary (Figs. 10.2a and 10.3a). At salinity = 10, for example, recent DIN concentrations were 100 μmol L^{-1} in the East China Sea and ~140 μmol L^{-1} in Hanghzou Bay.

The decadal variations of Hangzhou Bay DIP (Fig. 10.3b) are more complex than those of DIN. The majority of DIP concentrations measured in the 1980s were lower than those seen at the same salinities during the 2000s, but an exception is seen in the extremely high concentrations of some samples collected in winter 1981 (2.5–3.0 μmol L^{-1}). The processes regulating DIP concentrations are also more complicated those associated with DIN, with DIP being strongly influenced by not only Qiangtang River outflow and Changjiang plume intrusion, but also adsorption and desorption of DIP onto and off of suspended particles (Edmond et al. 1985).

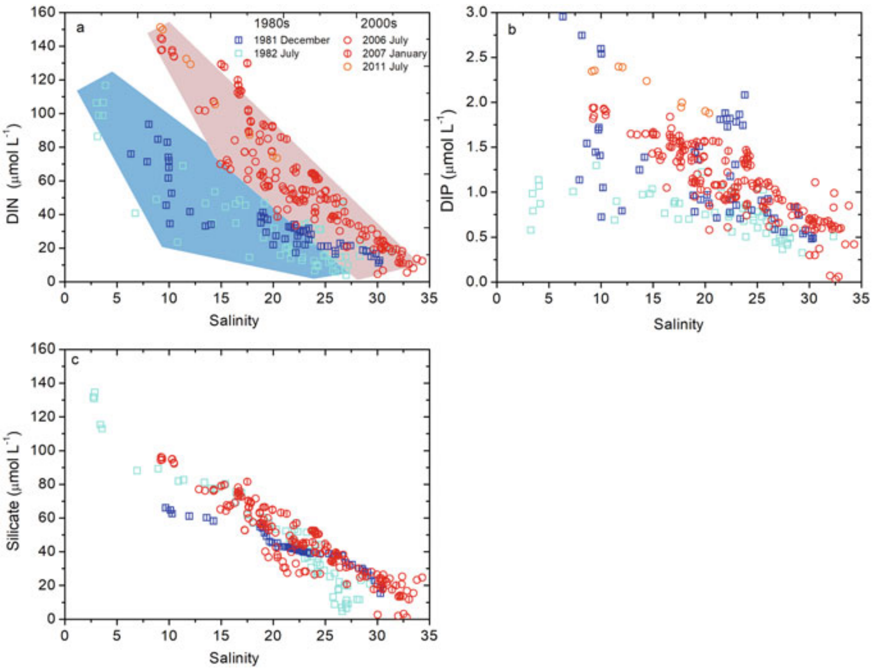

Fig. 10.3 Nutrient concentrations in Hangzhou Bay during the 1980s and 2000s, plotted as a function of salinity: **a** DIN, **b** DIP, and **c** silicate. The blue and red envelopes on panel (**a**) showed concentration limits along salinity during 1980s and 2000s, respectively. Data were obtained from Gao et al. (1993), Wang et al. (2011), Tseng et al. (2013) and Wu et al. (2019)

Both DIN and DIP are influenced by strong tidal mixing within the bay, which results in sediment resuspension and the mixing of nutrients released from the sediment pore waters. Sediment suspension also contributes extreme high particulate organic carbon flux (720–7300 mg C m^{-1} day^{-1}) in the inner shelf of the East China Sea (Hung et al. 2013), which could possibly enhance nutrient regeneration. The role of tidal resuspension on decadal nutrient variations in the bay are largely unknown.

For silicate concentrations in Hangzhou Bay, there was no obvious decadal concentration trend (Fig. 10.3c), similar to the case of the East China Sea.

10.2.3 N/P and N/Si Ratios

In East China Sea coastal waters, extremely high N/P ratios were measured, due to the inflow of high-N/P Changjiang river waters. Classical biogeochemical theory suggests that phytoplankton take up nutrients with a N/P ratio of 16 (Redfield 1958), with slight variations in different systems (Anderson and Sarmiento, 1994; Deutsch and Weber 2012). In both the 1980s and the 2000s, the N/P ratios of most East China

Sea water samples were well above the Redfield ratio (Figs. 10.4a, c) (Harrison et al. 1990; Tseng et al. 2013; Wang et al. 2013a, b). For waters of salinity <15, N/P ratios in the 2000s (~60) were lower than in the 1980s (~100). However, it is hard to say whether this decrease was ecologically significant because even the later N/P ratios were still much greater than 60. For waters of salinity >25, N/P ratios can be much higher than those seen in low-salinity waters because of the intense phytoplankton uptake of phosphorus in marine waters (Wang et al. 2013a, b). For the most productive plume waters (salinity ranges from 25 to 31), the N/P ratio was sometimes >150, as DIP concentrations were usually below the detection limit of 0.01 μmol L^{-1}. It should be noted that Kuroshio Subsurface Water significantly influences the chemical characteristics of subsurface water on the Changjiang shelf. With an N/P ratio of ~16, Kuroshio Subsurface Water could potentially alleviate phosphate limitation in shelf waters (Chen 1996; Chen and Wang 1999; Li et al. 2016; Tseng et al. 2013).

The N/Si (DIN/silicate) ratio in the 1980s was ~0.5, doubling to ~1 by the 2000s (Fig. 10.4b, d). Such an increase can be explained by the steady increase of DIN over the decades (Chai et al. 2009; Li et al. 2007; Wang et al. 2018). It is usually assumed that silicate is not a limiting nutrient in the Changjiang estuary and the East China Sea. However, as the N/Si ratio increased, the phytoplankton community characteristic may be changed over time. Previous studies suggested that dinoflagellate increased

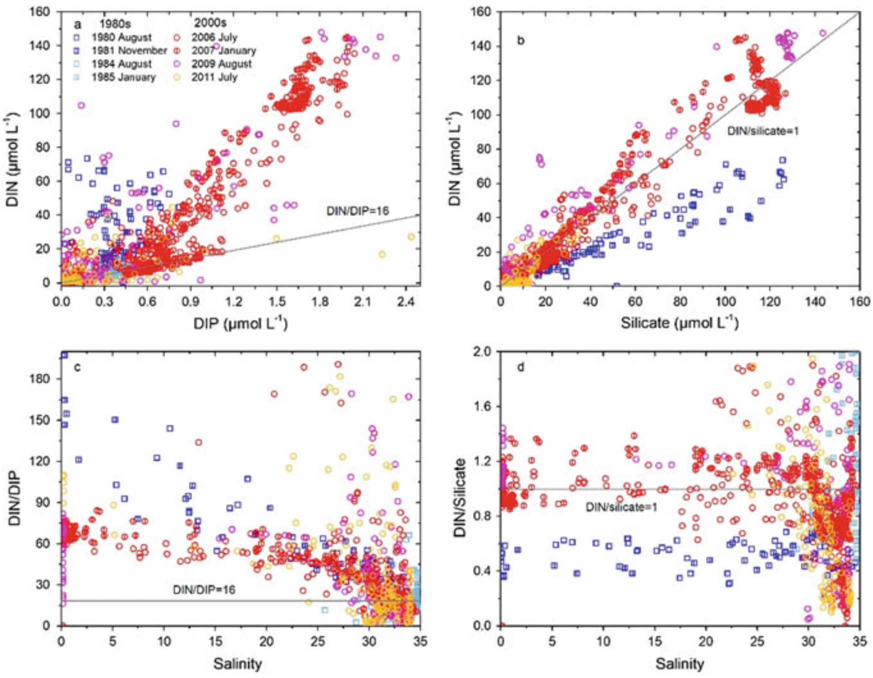

Fig. 10.4 Relationships between nutrtients in the East China Sea during the early 1980s and the 2000s: **a** DIN and DIP, **b** DIN and silicate, **c**, DIN/DIP and salinity, and **d** DIN/silicate and salinity

over past decades (Zhou et al. 2008, and discussion below). Notwithstanding, during the summer, diatoms (with shells of silica) are the dominant phytoplankton group in the Changjiang Estuary (Jiang et al. 2014), and remineralization of their sinking remains is the major consumer of bottom-water oxygen in the outer estuary (Wang et al. 2017a).

10.2.4 Changing Nutrient Inputs

Sources of nutrients to the East China Sea have been discussed in previous studies (Chen and Wang 1999; Kim et al. 2013; Liu et al. 2000 Zhang et al. 2007). Briefly, offshore waters are the major sources of phosphate and silicate to the shelf, with rivers contributing significant nitrogen (Chen and Wang 1999). For the Changjiang River plume waters specifically, nutrient dynamics are influenced mostly by riverine materials. The Changjiang River is the major supplier of fresh water.

Nutrient fluxes in the Changjiang River have risen sharply in recent decades (Fig. 10.5) due to increasing anthropogenic inputs (Dai et al. 2010; Li et al. 2007; Liu et al. 2003; Wang et al. 2018; Zhou et al. 2008). In the early 1960s, Changjiang DIN concentrations (as measured at the Datong hydrological station, approximately 624 km upstream from the river mouth) were ~20 μmol L^{-1} (Fig. 10.5a). Over the next 20 years there was little change, but in the 1980s DIN began to increase sharply. By the 1980s, concentrations had increased to ~80 μmol L^{-1}, and in the 2000s, values of 100–120 μmol L^{-1} were measured. The most recent measurements, from the 2000s, were ~120–160 μmol L^{-1}. A critical part of this story is the 1980s launch of the Reform and Opening policy by the Chinese government. Over the next four decades, the use of nitrogen fertilizer increased by a factor of about four in China (Liu et al. 2013).

DIP concentrations in the river (Fig. 10.5b) fluctuated around ~0.5 μmol L^{-1} before 1980, then increased sharply to ~1.5 μmol L^{-1} in the 1990s and ~1.5 μmol

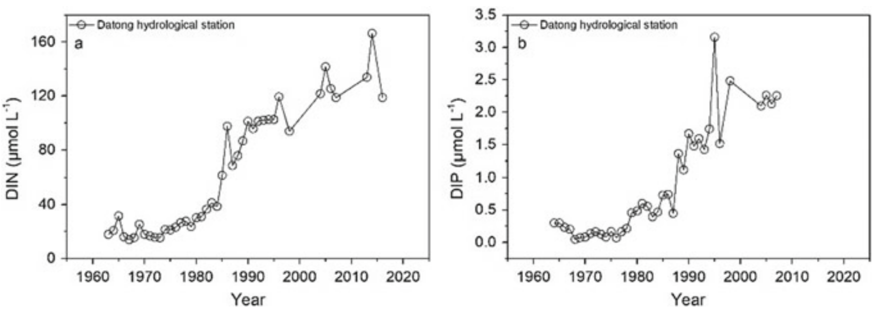

Fig. 10.5 Long term nutrient data in the Changjiang. **a** DIN, **b** DIP. Nutrient data in Datong hydrological station were obtained from Li et al. (2007) and Wang et al. (2018)

L^{-1} in the 2000s. As with DIN, increasing concentrations of DIP in the Changjiang River were caused by increasing anthropogenic inputs.

Surface offshore waters in the East China Sea (salinity > 34) are generally oligotrophic, with nutrient-rich subsurface waters beneath. When this deeper waters are upwelled onto the East China Sea shelf, massive amounts of nutrients are also transported onto the shelf (Chen 1996). Because subsurface upwelling and advection are strongly influenced by diverse events of various scales—such as meandering of the Kuroshio Current (James et al. 1999) and the passage of eddies and typhoons (Hsin et al. 2010)—decadal trends in offshore nutrient concentrations are difficult to evaluate from the available data. Lui et al. (2014), based on long-term nutrient data from the Japan Meteorological Agency, concluded that the nitrate concentration of Kuroshio Intermediate Waters at 400 m increased at a rate of 0.197 ± 0.0295 μmol kg^{-1} $year^{-1}$ (1987–2010) due to reduced ventilation of North Pacific Intermediate Water. The influence of increasing nutrient concentrations in source waters to the East China Sea shelf merit further study, especially in the context of ongoing global change.

10.3 Phytoplankton Communities

Eutrophication profoundly influences phytoplankton communities, and has led to an increase in the occurrence of harmful algal blooms in the China coastal seas (Jiang et al. 2014; Wang and Wu 2009; Zhou et al. 2008), thereby exacerbating hypoxia in terms of its frequency, range, persistence, and destructive capability (Wang et al. 2017; Zhu et al. 2011). Understanding long-term changes in phytoplankton communities is useful in the assessment and management of large estuaries and marginal seas. Several studies have reported phytoplankton community variations in the Changjiang Estuary in response to environmental forcing (Li et al. 2010; Jiang et al. 2010; 2014; Zhou et al. 2008), but few studies have focused on phytoplankton community change across the entire East China Sea.

Since 1958, a large number of phytoplankton studies have been conducted using plankton nets (76 μm mesh) in the Changjiang Estuary and East China Sea (Guo and Yang 1992; Jiang et al. 2014 and references therein; OIOSC 1964b; Zheng et al. 2003). In accord with Chinese government's specifications for marine monitoring, most early phytoplankton collections in the area were conducted using this type of net, and until recently, few samples were collected using water sampling (Jiang et al. 2014 and references therein).

Early phytoplankton studies in the Changjiang Estuary were conducted mostly during summer (Huang et al. 2018; Jiang et al. 2014 and references therein). This section therefore focuses on summer phytoplankton community variations in the Changjiang Estuary from 1959 to 2016, as seen in net-collected phytoplankton samples. Such samples likely reflect time-of-collection losses of noncolonial species with small cell sizes (e.g., cryptophytes, coccolithophores, and some diatoms and dinoflagellates). We also compiled data regarding phytoplankton communities in the

East China Sea during other seasons, 1958–2011. We examined changes in abundance, dominant species, and community composition of phytoplankton using net collection method. Our objective was to explore phytoplankton community change in the Changjiang Estuary and East China Sea in response to extensive human activity and ongoing climate change.

10.3.1 Phytoplankton Abundance

Over the period of record for the Changjiang Estuary, the abundance of net-collected phytoplankton (1959–2016) increased significantly (Mann-Kendall test, $Z = 2.26$; $p < 0.05$) (Fig. 10.6). In the East China Sea as well (Table 10.1), net-collected phytoplankton abundance (1958–1959 to 2009–2011) increased, with large variations among the different seasons. These results are consistent with reports of increased

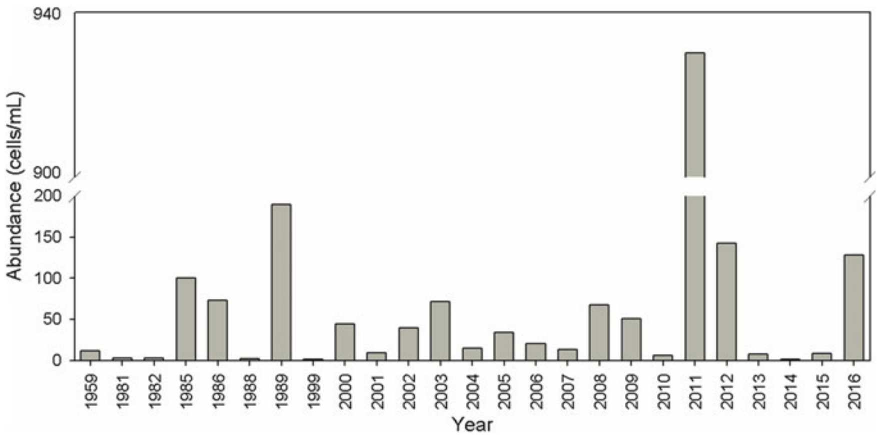

Fig. 10.6 Time-series of abundance of net-collected phytoplankton from the Changjiang Estuary, 1959–2016 (approximately 30–32°N, 121.5–124°E). Data were obtained from Huang et al. (2018), Jiang et al. (2014) and references therein, and also our own unpublished results

Table 10.1 East China Sea phytoplankton abundance (cells L^{-1}), based on net-collected samples. Data were obtained from Liu et al. (2015a), Zheng et al. (2003), and our own unpublished results

Year	Winter	Spring	Summer	Autumn	Average
1958–1959	–	–	–	–	1120
1981–1982	120	1400	12000	1700	3805
1997–2000	114	20	504	2119	689
2006–2007	908	5290	50200	18400	18700
2009–2011	831	816	17266	8814	6932

concentrations of chlorophyll *a* in both field measurements (Jiang et al. 2014) and remote-sensing studies (He et al. 2013). Previous studies have linked increased phytoplankton biomass to the nutrient enrichment of recent decades (Jiang et al. 2010, 2014; Zhou et al. 2008).

10.3.2 Phytoplankton Community Composition

In the Changjiang Estuary, the contribution of diatoms to phytoplankton cell abundance has decreased in recent decades (Mann-Kendall test, $Z = -1.09$), while the contribution of dinoflagellates has slightly increased (Mann-Kendall test, $Z = 0.33$) (Fig. 10.7a). Similarly, the proportion of diatom species within the total number of species has decreased (Mann-Kendall test, $Z = -2.26$, $p < 0.05$) while the proportion of dinoflagellate species has increased (Mann-Kendall test, $Z = 1.86$) (Fig. 10.7b). In the East China Sea (Fig. 10.8), the story is the same: decreasing dominance of diatoms and increasing dominance of dinoflagellates. This widespread community shift is likely attributable to changing nutrient ratios and rising water temperatures. In the Changjiang Estuary and elsewhere, under conditions of increased DIN/Si (Fig. 10.4) and regional warming (Belkin 2009; Jiang et al. 2014), non-siliceous phytoplankton, particularly dinoflagellates, have gradually became more dominant (Jiang et al. 2010; 2014; Sellner et al. 2001).

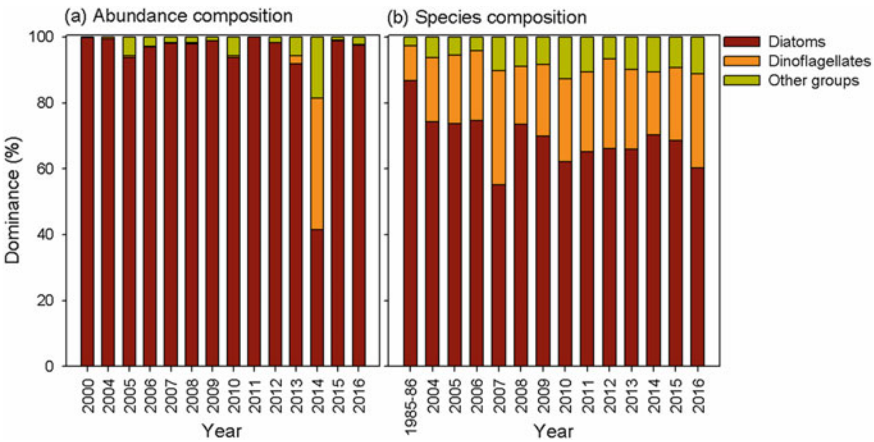

Fig. 10.7 Time-series of community composition of net-collected phytoplankton from the Changjiang Estuary (approximately 30.5–32°N, 121.5–123°E): percent occurrence in terms of **a** cell numbers, 2000 to 2016 and **b** species numbers, 1985–1986 to 2016) Data were obtained from Guo and Yang (1992), Huang et al. (2018), Wang et al. (2008), and our own unpublished results

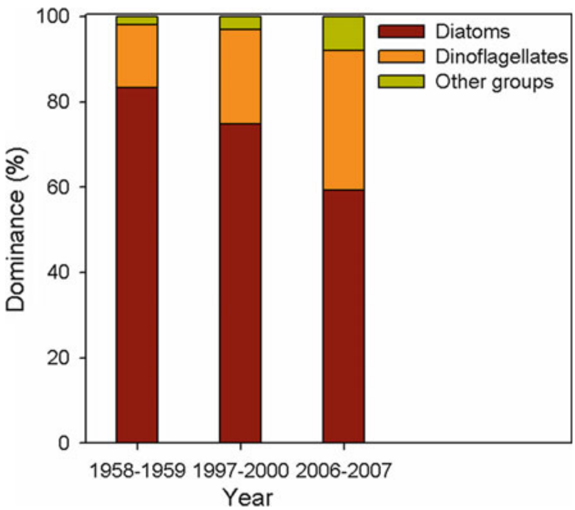

Fig. 10.8 Time-series of species composition of net-collected phytoplankton from the East China Sea. Data were obtained from OIOSC (1964b), Zheng et al. (2003), and our own unpublished results

10.3.3 Dominant Phytoplankton Species

In the Changjiang Estuary, the dominant species (dominance here is calculated the same as percentage) in the summertime phytoplankton samples (net-collected) have most consistently been the chain-forming diatoms, mainly within the genera *Skeletonema*, *Chaetoceros*, and *Pseudo-nitzschia* (Table 10.2). Recently, the proportions of large-celled dinoflagellates (*Ceratium*) and filamentous cyanobacteria (*Trichodesmium*) have been growing, although their percentages are still small. In the East China Sea, recent phytoplankton samples have been similarly dominated by colonial diatoms, dinoflagellates (e.g., *Ceratium* spp., *Dinophysis caudata*, *Noctiluca scintillans*, and *Prorocentrum donghaiense*), and *Trichodesmium* spp. (Table 10.3). Despite the eutrophication occurring in the Changjiang Estuary and East China Sea (Fig. 10.2 through Fig. 10.5), the trichome densities of *Trichodesmium* (which usually thrives in oligotrophic warm waters) have increased considerably in both areas (Jiang et al. 2017, 2018), In addition, the northern range boundary of this warm water species has shifted northward since the 1970s (Jiang et al. 2018). We therefore speculate that the shifts of dominant species seen in the Changjiang Estuary and East China Sea are closely related to not only eutrophication but also warming.

Table 10.2 Changjiang Estuary summertime phytoplankton species dominance, 1959–2011 (30–33°N, 122–124°E; net-collected). Diatom species are listed in red, dinoflagellates in organge, and cyanobacteria in green. The grid-cell colors indicate percent dominance, with warmer colors indicating greater dominance (see key at end of table). Data were obtained from Jiang et al. (2014) and references therein, as well as our own unpublished results

Species	1959	1960	1982	1988	1989	1999	2003	2006	2007	2009	2011
Chaetoceros affinis						<2%				2-5%	2-5%
Chaetoceros compressus										2-5%	
Chaetoceros costatus											2-5%
C. curvisetus							10-20%		20-50%		
C. debilis											2-5%
Chaetoceros decipiens						<2%					
Chaetoceros denticulatus										2-5%	
Chaetoceros denticulatus f. *angusta*										5-10%	
Chaetoceros diadema							10-20%	2-5%			
Chaetoceros paradaxus										2-5%	
C. pseudocurvisetus						50-80%				2-5%	2-5%
C. lorenzianus				10-20%	<2%	2-5%	5-10%		10-20%	5-10%	5-10%
Chaetoceros spp.	2-5%										
Coscinodiscus spp.				2-5%	<2%						
Eucampia zoodiacus				20-50%	<2%						
P. alata f. *gracillima*						10-20%		10-20%			
P. pungens	5-10%			20-50%	<2%		2-5%		10-20%	10-20%	2-5%
Rhizosolenia styliformis										10-20%	
Skeletonema spp.	>80%	>80%	50-80%	2-5%	>80%	>80%	20-50%	50-80%	10-20%	<2%	>80%
T. nitzschioides								5-10%			
T. subtilis			20-50%								
T. frauenfeldii										2-5%	
Ceratium tripos											<2%
Trichodesmium thiebautii										2-5%	
Trichodesmium hildebrandtii										2-5%	

Non-dominant | <2% | 2-5% | 5-10% | 10-20% | 20-50% | 50-80% | >80%

Table 10.3 East China Sea dominant phytoplankton species by season, 1958–2011 (net-collected). Diatom species are listed in red, dinoflagellates in organge, and cyanobacteria in grey. The seasons are indicated by W (winter, shaded by blue), Sp (spring), Su (summer, shaded by red), and A (autumn). The green color blocks mark which species were dominant in each time segment. Data were obtained from Liu et al. (2015a) and Zheng et al. (2003)

Species	1959				1981				1997-2000				2009-2011			
	W	Sp	Su	A	W	Sp	Su	A	W	Sp	Su	A	W	Sp	Su	A
Bacilari paxillifera													■			
Cerataulina spp.								■								
C. curvisetus																■
C. debilis		■														■
Chaetoceros decipiens												■				
C. lorenzianus									■	■	■		■		■	■
C. pseudocurvisetus									■							
Chaetoceros spp.	■			■											■	
Coscinodiscus spp.				■									■			
Paralia sulata													■	■		
Pseudo-nitzschia delicatissima															■	
P. pungens		■			■	■	■								■	
P. alata f. *gracillima*							■				■	■				
Skeletonema spp.		■			■	■	■				■				■	
T. nitzschioides			■	■	■			■					■		■	■
T. subtilis	■								■	■		■				
Thalassiosira spp.													■	■	■	■
T. frauenfeldii	■															
C. tripos														■		
Dinophysis caudata														■		
Noctiluca scintillans														■		
Prorocentrum donghaiense														■		
Trichodesmium spp.													■	■	■	■

10.4 Dissolved Oxygen and Hypoxia

10.4.1 Dissolved Oxygen

DO concentration is controlled by the thermophysical properties of seawater (temperature, salinity, and pressure) and physical/biogeochemical processes such as diffusion and aeration, photosynthesis, and respiration. Globally, oxygen concentrations have been declining faster in coastal waters (-0.28 μmol L^{-1} $year^{-1}$) than in open ocean waters (-0.02 μmol L^{-1} $year^{-1}$) (0–300 m depth, 1976–2000; Gilbert et al. 2010). Changing ocean circulation, mixing, and biogeochemical processes (rather than direct thermally induced solubility effects) are the main drivers (Ito et al. 2017; Keeling et al. 2010). In coastal waters, deoxygenation is exacerbated by global warming (Keeling et al. 2010; Meier et al. 2011) and anthropogenic inputs of excess nutrients (Breitburg et al. 2018; Fennel and Testa 2018; Laurent et al. 2018).

DO in the East China Sea has been declining, just as in other seas around the world. Along a 32°N transect (122°–127°E), average annual rates of change of DO (1975–1995) were -0.448 (surface samples), -0.608 (water column samples), and -0.736 μmol kg^{-1} $year^{-1}$ (bottom samples) (Ning et al. 2011). At the sea surface, declining concentrations were due mainly to rising temperatures, which decreases oxygen solubility. At the sea bottom, declining concentrations were due mainly to biologically mediated summertime oxygen depletion, which was triggered by surface phytoplankton blooms and the subsequent sinking and remineralization of organic matter (Ning et al. 2011). Estimated summer bulk oxygen depletion in the hypoxic bottom water (based on absolute apparent oxygen utilization, AOU, relative to the fully saturated state) was 4.7×10^6 tons DO in 1999, 7.2×10^6 tons in 2006, and 5.1×10^6 tons in 2013 (Zhu et al. 2017). On the outer shelf, estimated rates of DO change in Kuroshio Intermediate Water (1982–2010) ranged from -0.11 ± 0.07 to -0.19 ± 0.02 μmol kg^{-1} $year^{-1}$ (based on data from line PN: 126°E, 29°N to 128.3°E, 27.5°N). This decline was caused by reduced ventilation of North Pacific Intermediate Water (Lui et al. 2014), where DO had a maximum rate of decline (1985–2010) of -0.36 ± 0.08 μmol kg^{-1} $year^{-1}$ on the potential density surface of $\sigma = 27.3$ (Takatani et al. 2012). The DO of Kuroshio Tropical Water has, despite the effects of warming and freshening, increased due to enhanced productivity (Lui et al. 2014).

10.4.2 Seasonal Hypoxia

Bottom hypoxia occurs frequently in estuaries and coastal waters where high rates of photosynthetic production contribute massive amounts of organic matter to bottom waters. This input of organic carbon results in high rates of oxygen consumption in the subsurface waters and sediments. Such hypoxia can be exacerbated by global warming (Keeling et al. 2010), decreasing ocean ventilation, and, mostly importantly, the eutrophication of coastal waters (Liu et al. 2015a, b), which is caused by increasing nitrogen fertilizer usage and sewage inputs (Breitburg et al. 2018; Diaz and Rosenberg 2008; Zhang et al. 2010).

Hypoxia in the Changjiang Estuary occurs below the pycnocline and is seasonal in character. Low-oxygen conditions develop in late spring and early summer, reaching maximum spatial extent during mid-summer or sometimes early autumn, and then disappearing in late autumn (Li et al. 2011; Wang et al. 2012). Usually, there are two zones of hypoxia: one off the Changjiang Estuary and inner Subei Shoal and one near the Minzhe coastal area (Fig. 10.9). The northern zone is likely associated with low-salinity water detached from the Changjiang Diluted Water (Xuan et al. 2012). The southern zone is in an area influenced by the upwelling of Kuroshio Subsurface Water. Oxygen depletion in the northern zone is severe but short-lived, whereas depletion in the southern zone is milder but longer in duration (Zhu et al. 2011). At Subei Shoal, hypoxic waters are found at depths shallower than 20 m and are usually well mixed vertically (Luo et al. 2018; Zhou et al. 2017). Outside the shoal area, the northern hypoxia occurs in waters deeper than 30 m (depth of ~45 m).

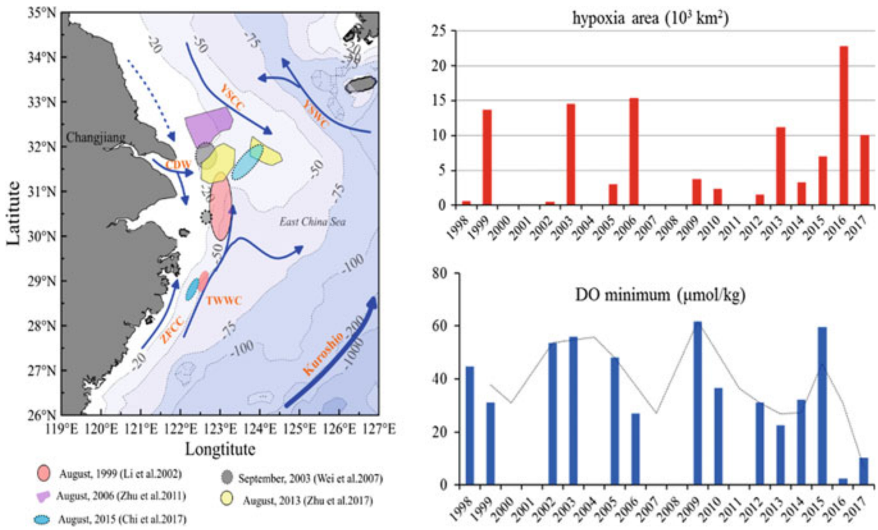

Fig. 10.9 Hypoxia in the East China Sea. **a** Map of East China Sea bathymetry and observed large (>5000 km^2) areas of hypoxia, 1999–2013. The blue arrows show major currents in the East China Sea: CDW = Changjiang Diluted Water, YSCC = Yellow Sea Coastal Current, YSWC Yellow Sea Warm Current, ZFCC = Zhejiang-Fujian Coastal Current, and TWWC = Taiwan Warm Current, and Kuroshio. **b** Time series of hypoxia areal extent, 1998–2017. **c** Time series of DO minima, 1998–2017. The dotted gray line shoes moving average result of the data. For events before 2013, data were obtained from Zhu et al. (2011) and Luo et al. (2018) and references therein. For years 2014, 2016, and 2017, data were obtained on recent field cruises (unpublished data, Jianfang Chen, principal investigator). For 2015, data were obtained from Chi et al. (2017)

Summer hypoxia in the vicinity of the estuary (in areas centered at 31.5°N, 123°E) was first reported in the late 1950s and 1960s, with an average coverage of 3,000–4,000 km^2 (Wang et al. 1991). In the summer of 1999, Li et al. (2002) found a much larger hypoxic area of 13,700 km^2 (Fig. 10.9a). Since the 1990s, many researchers have reported an increasing incidence of hypoxia and adverse effects (Zhu et al. 2011 and references therein).

Large areas of hypoxia (>5,000 km^2) occurred in years 1999, 2003, and 2006, with smaller events every 3–4 years (Fig. 10.9b). Between 2009 and 2012, while nutrient inputs continued to increase, three more events of smaller extent were observed. In August 2013, a hypoxic area of 11,500 km^2 was documented (Zhu et al.2017). In 2016, the largest hypoxic area ever recorded, >22,808 km^2, was discovered during a late August research cruise. The following year, in August 2017, the hypoxic area was observed to be 10,071 km^2. These two recent years were also a time of dramatically lower DO minimum values within the hypoxic areas (Fig. 10.9c). The DO minima approximately 10 years earlier were 27.0 $\mu mol\ kg^{-1}$ (2006) and 61.7 $\mu mol\ kg^{-1}$ (2009). The 2016 and 2017 minimum values were 2.5 $\mu mol\ kg^{-1}$ and 10.2 $\mu mol\ kg^{-1}$, respectively.

Recent studies have linked this seasonal hypoxia to water-column stratification (Zhou et al. 2009; Zhu et al. 2016), bottom bathymetry (Wang et al. 2012), water residence time (Rabouille et al. 2008), upwelling of subsurface water (Chen et al. 2007), lateral advection (Wei et al. 2007), decomposition of marine-origin particulate organic matter (Chen et al. 2007; Wang et al. 2017a), and sedimentary oxygen comsumption (Song et al. 2016; Zhang et al. 2017). Bottom hypoxia has usually been coupled with the presence of Changjiang plume water and surface phytoplankton blooms (Chen et al. 2017), specifically diatom blooms (Wang et al. 2017a). As shown in the conceptual model of Fig. 10.10, waters in the outer region (seaward of the turbidity maximum zone) are clear; thus, light limitation of phytoplankton growth is alleviated. When nutrients and light are both suitable for algal growth (Ning et al. 2004), phytoplankton blooms, especially diatom blooms, consume dissolved nutrients and carbon dioxide (CO_2) in surface waters through photosynthesis. The result is deficits of nutrients and dissolved inorganic carbon and oversaturation with respect to oxygen. With strong summer stratification, organic matters (mostly contributed by diatom blooms in the East China Sea) sink quickly to the sea bottom, where they decompose and deplete oxygen from the bottom water. If oxygen consumption exceeds supply, the bottom waters will become hypoxic. In this way, surface blooms and bottom hypoxia are strongly coupled (Wang et al. 2017a). The occurrence of diatom blooms could thereby be a determining factor for the development of summer hypoxia in the East China Sea.

The full story is complex, though, with hypoxia in this marginal sea being highly dynamic and episodic. Disturbance by one of the frequent episodic events of summer (e.g., strong northeast winds, typhoons, tides, or eddies) may destroy one episode of hypoxia (Ni et al. 2016) while also triggering the onset of a subsequent one by mixing bloom-fueling nutrients upward from bottom waters into well-lit surface waters. Thus, hypoxia in the East China Sea, while seasonal in character, also displays highly dynamic spatial and temporal variations within the summer season.

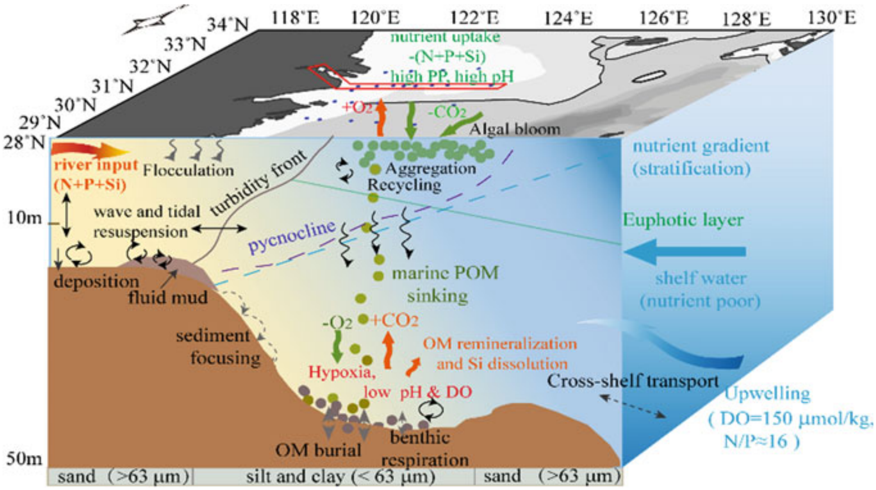

Fig. 10.10 Conceptual model for the formation of summer hypoxia in bottom waters due to surface diatom blooms off the Changjiang Estuary. Under optimal conditions of light and nutrients, diatom blooms may form, with high primary production in surface waters and large fluxes of rapidly sinking biogenic silica and labile organic carbon. Other potentially significant physical and biogeochemical processes include riverine input, aggregation, flocculation, desorption, resuspension, respiration, and intrusion (upwelling) of Kuroshio Subsurface Water. OM = organic matter Figure reproduced from Wang et al. (2017a)

Predicting future hypoxia remains difficult. Integrated multidisciplinary approaches are required to advance the current understanding of oxygen dynamics in the East China Sea.

10.5 Conclusions

Decadal average concentrations of DIN and DIP have significantly increased in the East China Sea and Hangzhou Bay since 1980s, especially in waters of salinity <31. At the outer edge of the Changjiang plume water (defined by salinity = 31), the maximum DIN concentration was ~16 μmol L^{-1} in the 1980s and ~25 μmol L^{-1} in the 2000s. DIN concentrations in waters of salinity >33 did not exhibit notable decadal change. DIP concentrations (for a given salinity) in the East China Sea were higher in the 2000s than the 1980s. Silicate concentrations did not exhibit notable decadal change. Some nutrient ratios changed. The DIN/silicate ratio doubled, from ~0.5 in the 1980s to ~1 in the 2000s. The dramatic decadal changes of nutrient concentrations and ratios were caused mostly by increasing DIN and DIP concentrations in the Changjiang River.

Phytoplankton communities in the Changjiang Estuary and East China Sea have experienced remarkable changes. The overall phytoplankton abundance increased over the past 50 years. In the 1950s and the 1980s, chain-forming diatoms were the dominant species. In recent years, large-cell dinoflagellates and filamentous cyanobacteria have been growing, although their percentages are still small. All of these changes are strongly associated with eutrophication and warming, but quantitatively defining those linkages is difficult because of the limited availability of time-series data. These changes in phytoplankton community structure may profoundly influence local food-web dynamics and biogeochemical processes, thus exacerbating the occurrence of harmful algal blooms and hypoxia in the Changjiang Estuary and East China Sea.

DO concentrations in the East China Sea have been generally declining due to global warming and eutrophication. Reduced regional ventilation and the remineralization of the products of locally boosted productivity have together tended to promote oxygen depletion. Before 2013, summer hypoxia in the East China Sea was relatively limited in terms of spatial coverage and severity. In 2016, hypoxia occurred over an expanded area of the sea (>22808 km^2), with dramatically lower values of minimum DO (~2.5 μmol L^{-1}). Occurrences of hypoxia are highly dynamic and are tied to a variety of events over a wide range of scales. Therefore, multidisciplinary approaches are required to evaluate present conditions and predict future changes. Summer hypoxia is affected by both climate change and anthropogenic activity.

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